Appendix C
Summary of the Hydrogeologic Flow Model for Tooele Army Depot, Utah

A summary of the steps taken in the computer model development for the Tooele Army Depot follows. This summary serves as an example of what is involved in a site characterization using computer modeling techniques. The original document is not reproduced in its entirety; the most important details for each section are mentioned, using the table of contents from the original document as the format.

1 Introduction

1.1 Abstract 1

A three-dimensional finite difference flow model was used to simulate groundwater flow at a TCE-contaminated site within the Tooele Army Depot in Utah.

1.2 Acknowledgements 1

1.3 Background 2

The groundwater below the site was contaminated by trichloroethylene (TCE) flowing through four unlined ditches to an unlined industrial waste lagoon. The Corps was requested to develop a groundwater flow model incorporating the most reliable past and current data from a number of wells installed onsite for application to system design enhancement.

Figure 1. Location Map
Figure 2. Project Site Map

1.4 Purpose and Scope 2

The primary objective of this modeling effort is to provide a tool for determining scientifically based optimum pumping rates and locations which will ensure the hydrodynamic isolation of the TCE plume below and to the north of the closed Industrial Waste Lagoon (IWL). The model should also have the ability to reflect hydrogeologic responses of future stresses placed upon the site under various potential scenarios, i.e., the impact of future extraction or injection wells at various site locations on flow direction, flow velocity, and contaminant containment.

2 Regional Geology and Hydrology

2.1 Topography 7

The Tooele Valley encompasses approximately 250 square miles within a 400-square-mile drainage basin. It is bordered by the Oquirrh Mountains on the east, by the Stansbury Mountains on the west, and by South Mountain and Stockton Bar on the south. To the north, the valley fronts on the Great Salt Lake.

2.2 Climate 7

The climate of the Tooele Valley drainage basin ranges from semiarid in the salt flats near the Great Salt Lake to humid in the higher mountains. The average precipitation at the town of Tooele for the period 1897-1977 is 16.49 in.

Figure 3. Normal Annual Precipitation of Tooele Valley

2.3 Regional Geology 7

The Tooele Valley is typical of the basin and range physiography in which fault block mountains rise above flat, intermontaine valleys (Figure 4). The bulk of this valley fill consists of inter-fingering clays, silt, sand, and gravel. The fill was emplaced in a complex sedimentation pattern of lake bottom, lake shore, stream, and alluvial fan deposits, making it difficult to correlate beds from one part of the valley to another (38). There are areas of faulting and folding.

Figure 4. Geologic Map of Tooele Valley

2.4 Regional Hydrology 8

Groundwater in the Tooele Valley drainage basin occurs in the consolidated rocks of the mountains and in the unconsolidated valley fill. As shown in Figures 5 and 6, regional groundwater flow trends from the mountain recharge areas towards the northern valley front with the Great Salt Lake.

Figure 5. Regional Groundwater Flow of Tooele Valley
Figure 6. Regional Groundwater Table of Tooele Valley

3 Development of Conceptual Model

3.1 Data Acquisition 12

From 1982-1992, 162 monitoring wells and piezometers were installed at the TEAD study site to help characterize potentiometric surfaces, groundwater flow directions, hydraulic gradients, and chemical characteristics (Appendices B, C, and H). Additional hydrogeologic information on the Tooele site indicated evidence of faulting on the northern and western areas of the uplifted bedrock block.

3.2 Geologic Framework 12

Two physiographic features dominate site geology: an uplifted bedrock block of quartzite, sandstone, and limestone located beneath and to the northeast of the IWL, and unconsolidated, poorly sorted alluvial deposits of varying thickness located to the north, west, and south of the bedrock. Extensive, yet highly variable fracturing exists throughout the bedrock system.

Figure 7. Transverse Hydrogeologic Sections
Figure 8. Longitudinal Hydrogeologic Sections

3.3 Hydrologic Framework 17

Groundwater flow trends in a northwest direction across the TEAD site (Figures 5 and 6). Broadly speaking, the TEAD study site can be divided into three separate hydraulic units: the steep flow gradients of the fractured bedrock and adjoining low conductive (low K) alluvium in the central area of the site, the highly transmissive alluvium to the north, and the shallow alluvium at the southern, upgradient end of the site. The uplifted, fractured bedrock block and adjoining low conductive alluvium are the hydraulically controlling features of the study area due to the steep gradients required for flow across this area.

Figure 9. Observed Groundwater Table

3.4 Groundwater Quality 19

TCE is considered to be the contaminant of primary concern. The plume, defined by the 5-µg/ℓ isoconcentration contour was estimated by JMM to be 400 ft thick and to contain an estimated 36 billion gallons of groundwater (11). JMM (11) estimated the rate of movement of groundwater in the contaminated area to range from 700 to 1,200 ft/year in the areas of greatest groundwater flow velocity.

3.5 Hydraulic Properties 21

Field measurements of hydraulic conductivity show a broad variance from less than 1 ft/day in the bedrock areas, to over 1,000 ft/day in the northern alluvium (11,12,41). The wide range of hydraulic conductivity values derived from tests provided additional evidence of the heterogeneous nature of the alluvium on a local scale.

4 Computer Code

4.1 Selection Criteria 23

The purpose of the TEAD groundwater model is to serve as a practical aid in the design of a pump-and-treat system.

4.2 Model Selection 23

The U.S. Geological Survey (USGS) models MODFLOW and MODPATH were judged to best meet the criteria and were thus selected for use in the TEAD groundwater modeling project.

4.3 Accompanying Models 26

A computer program for calculating sub-regional water budgets using results from MODFLOW (47) will be included in the modeling package to allow the user to easily determine volumetric flow budgets in specified sub-regions of the modeled area. Additionally, a computer program was written which estimates steady-state drawdown at a pumping well using output from MODFLOW (Appendix I).

4.4 Accompanying Software 26

5 Construction of Groundwater Flow Model

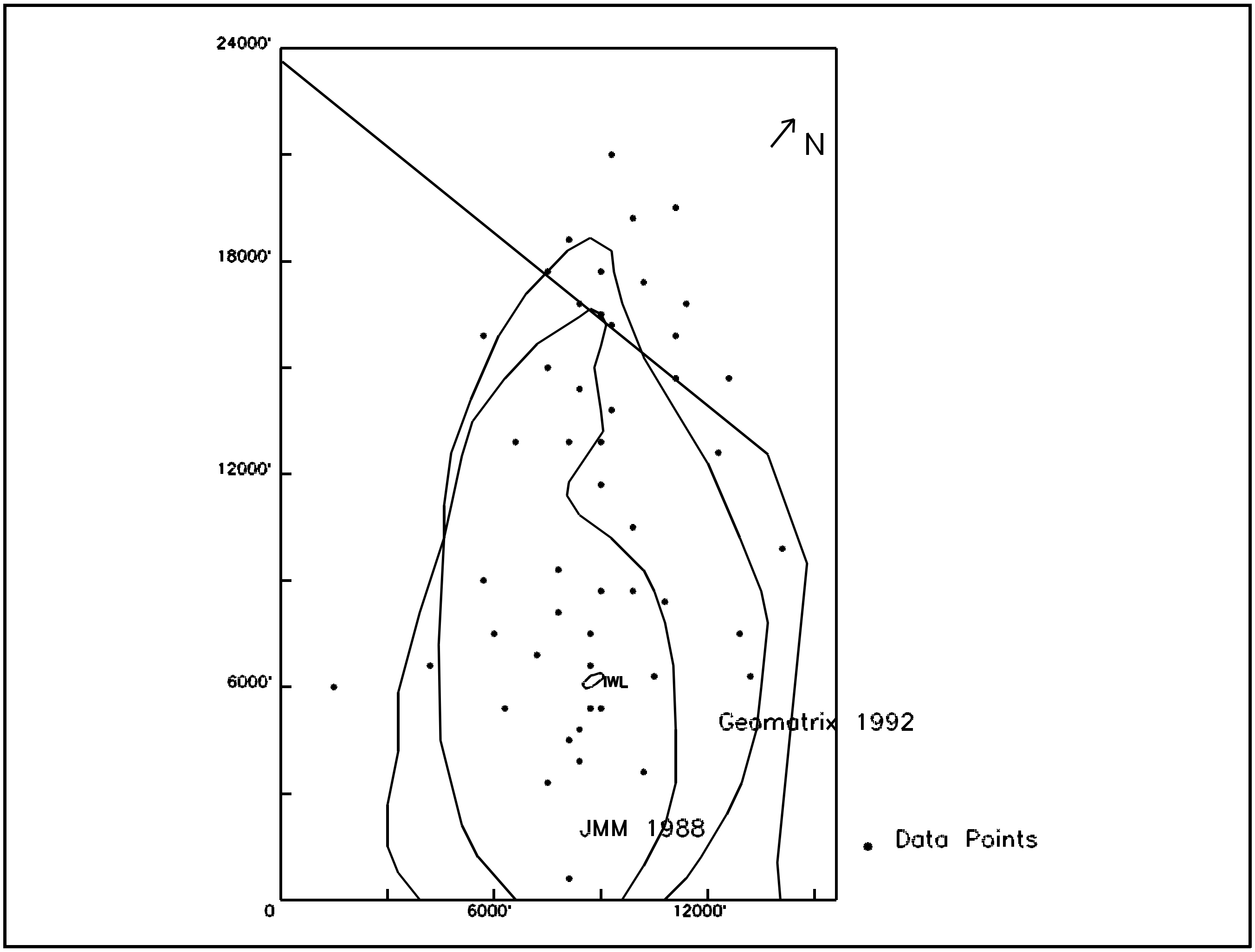

Figure 10. Migration of TCE Plume, Tooele Army Depot

5.1 Initial Two-Dimensional Model 27

The modeling effort proceeded in a deliberate fashion from a simple two-dimensional grid aligned with the observed groundwater flow direction to the final 52 × 80 three-dimensional grid. A constant head boundary, corresponding to measured water level elevations, was located at the southeastern end of the site. A constant flux boundary, which represented the total flow through the site area, was located on the northwestern boundary.

5.2 Selection of Model Layers 27

Because of minimal evidence of well-defined continuous layering occurring in the alluvium, three layer divisions were selected to allow for the simulation of vertical head gradients measured across the site.

Figure 11. Model Layers

5.3 Creation of Final Model Grid 28

The model grid was oriented in a southeast-northwest direction with columns being oriented in the direction of groundwater flow (Figure 12, Plate 2). The grid area was designed to be large enough to encompass any pertinent data points and the extent of the contaminant plume, with the interior grid being fine enough to delineate the hydrologic structures and prevent the combination of two wells per grid cell. The final grid design was then entered into the MODELCAD pre-processor along with the surveyed locations of the wells (Appendix C) and oriented in the direction of groundwater flow.

Figure 12. Model Grid

5.4 Model Calibration 31

The model was calibrated using measured values. Some data values were varied through multiple model runs to best characterize the site.

Table 1. Water Level Vertical/Horizontal Corrections for Model Calibration

5.5 Solution Convergence 33

The Strongly Implicit Procedure (SIP) was used to iteratively solve for unknown heads at each grid cell. The goal of this modeling effort is to consistently produce a mass balance input/output flow differential of less than 0.1 percent.

Figure 13. Location of Water Level Calibration Points

6 <u>Boundary and Initial Conditions</u>

Initial boundary conditions consisted of a constant head boundary at the southeastern side of the grid, a constant flux boundary at the northwestern end of the model grid, and no-flow boundaries on the northeastern and southwestern sides of the model grid. A constant recharge rate was assigned to all cells in the upper model layer to simulate infiltration from precipitation. The base of the lower model layer was simulated as a no-flow boundary. Flow across this boundary is assumed to be insignificant relative to the flow in the upper 600 ft of the system.

6.1 Constant Head Boundary 35

A constant head boundary specifies a potentiometric surface elevation at a given location which provides an unlimited supply of water depending on gradient and conductivity values of the system.

6.2 Constant Flux Boundary 35

The northwestern constant flux boundary regulates the total flow through the site. The flux boundary values were determined by first estimating the total flow through the modeled area, and then partitioning flow values among the three layers.

6.3 Head-Dependent Flux Boundaries 41

The solution to this problem is to, in effect, extend the model boundaries to the northwest and southeast through the use of head-dependent flux boundaries. The distance to extend the boundaries of model influence should correspond to the regional flow system, thus giving a more realistic response to groundwater discharge/recharge scenarios.

6.4 Recharge 43

According to Gates (34), precipitation on the TEAD site ranges from 13 in./year on the southeastern end to 11 in./yr. in the area of the northwestern boundary (Figure 3). Razem and Steiger (38) estimated the percentage of this amount of precipitation that infiltrates to groundwater to range from 1-3 percent.

6.5 Initial Conditions 43

After calibration under the no-action scenario, the steady-state head solutions were saved and used as starting heads in pumping scenarios for the purpose of computing drawdowns.

7 <u>Determination of Hydrogeologic Properties</u>

7.1 Hydraulic Conductivity 45

The TEAD site was divided into spatial zones of homogeneous hydraulic conductivity values. The complexity of the model was considerable to be commensurate with the ability of data to represent the system. Model results complement field evidence of the existence of a fault zone that is trending northeast to southwest along the northwest side of the bedrock (Figure 15).

Figure 14. Recharge Zones
Figure 15. Hydraulic Conductivity Zones, Layer 1
Figure 16. Hydraulic Conductivity Zones, Layer 2
Figure 17. Hydraulic Conductivity Zones, Layer 3
Table 2. Values of Hydraulic Conductivity

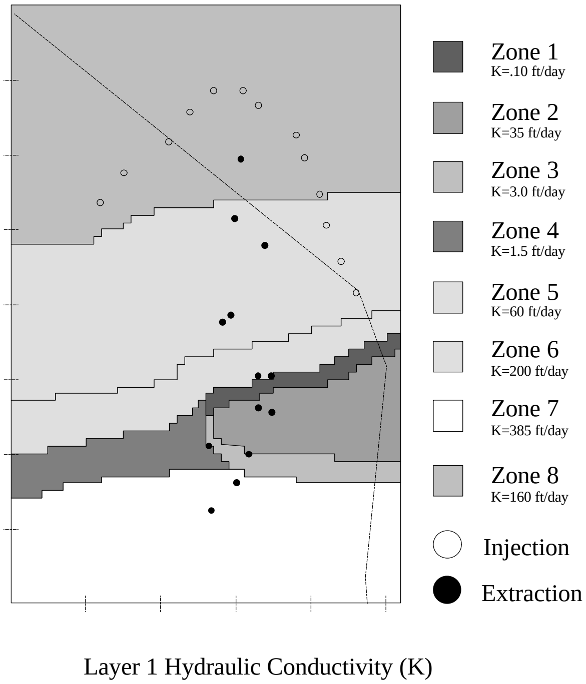

Figure 15. Hydraulic Conductivity Zones, Layer 1

Table 3. Extraction Well Data
Table 4. Injection Well Data

7.2 Leakance 54

Vertical hydraulic conductivity is a difficult characteristic of an aquifer system to measure or estimate, yet it is a sensitive and significant parameter for multi-layered models.

Figure 18. Leakance Zones, Layers 1-2
Figure 19. Leakance Zones, Layers 2-3

7.3 Storativity/ Porosity 57

Storage coefficient values were derived and entered in the MODELCAD preprocessor for future transient applications. Effective porosity was set equal to the specific yield value for each hydrologic soil type and was input into the MODPATH MAIN.DAT input file as a tool for determining particle flow velocities.

Figure 20. Storativity/Porosity Zones, Layer 1
Figure 21. Storativity/Porosity Zones, Layer 2
Figure 22. Storativity/Porosity Zones, Layer 3

8 Sensitivity Analysis

8.1 Sensitivity Analysis 63

Sensitivity analysis is used to measure the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters and boundary conditions. The accompanying changes in head values, relative to the calibrated head values, are then analyzed as a measure of the sensitivity of the model to that particular parameter. The systematic varying of calibrated flow parameters indicated that the most sensitive parameters in model calibration were the hydraulic conductivity values and the flows determined at the head-dependent flux boundaries.

9 MODPATH Input Parameters

9.1 Input Parameters 65

Input requirements for the MODPATH particle tracking program include the WELL and RCH packages used in the MODFLOW analysis, unformatted cell-by-cell flow budget and head files created by MODFLOW, zonal values of effective porosity, and the starting locations of particles (46). Effective porosity values were derived in the Storativity/Porosity section. Effective porosity values are directly proportional to the velocity of particle flow, and are thus important in determining particle locations at specified time increments.

10 Model Application

10.1 No-Action Scenario 67

Initially, the flow model was run under a no-action scenario to present a description of static water elevations, and particle flow paths.

Figure 23. No-Action Potentiometric Surface Elevation, Layer 1
Figure 24. Water Particle Migration Rate
Figure 25. Profile of Water Particle Pathlines, Layer 3

10.2 Well Field Optimization 70

Sixty-four computer runs were completed to optimize well pumping rates and ensure the simulated 100-percent capture of the 5-ppb TCE contaminant plume downgradient from the IWL. Much of the optimization process was performed by trial and error.

10.3 Recommendations 71

Installation of three additional wells (E13,14,15) was required for 100-percent capture of the 5-ppb TCE contaminant plume downgradient of the IWL (Figure 26).

Figure 26. Optimized Pumping Scenario, Layers 1-3
Table 5. Optimized Extraction Well Locations/ Pumping Rates/Drawdowns
Table 6. Optimized Injection Well Locations/ Pumping Rates/Drawdowns

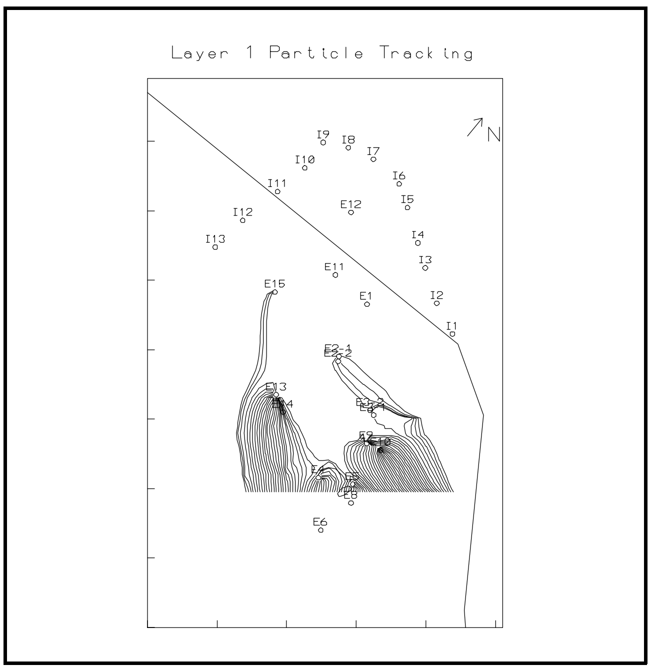

Figure 26. Particle tracking for optimization of plume removal, Layer 1

11 Additional Data Needs

11.1 Additional Data Needs 75

Additional data gathering should focus on further delineating the boundaries of the bedrock block, and providing additional physical evidence to corroborate the existence of displaced sediments.

12 Future Applications

12.1 Future Applications 76

Work on this project will continue as new field data are compared with simulated results. Future recalibration efforts should employ transient simulations as expanding cones of depression from pumping wells are compared with simulated water levels. The optimized pumping rates and well locations recommended in this report are for long-term steady-state capture of the contaminant plume. A transient, three-dimensional particle tracking computer program is in the final stages of development by the USGS. The application of this program to the Tooele site will enable the prediction of time requirements for complete capture of the contaminant plume, approximate percentage capture of the plume as a function of time, and will allow for the evaluation of transient capture efficiency by adding new wells. This model can be used to predict long-term effects of the pump-and-treat system on contaminant mitigation and overall project completion time requirements, and simulate the transport of contaminants off-site.

13 Conclusion

13.1 Conclusion 77

The three-dimensional finite-difference model MODFLOW (44) was selected to simulate groundwater flow across the TEAD site. The modeled area of 15,600 ft by 24,000 ft was overlain by a 52 x 80 grid of square cells 300 ft on each side. The model was constructed in three layers simulating unconfined and confined flow conditions. Boundaries of the flow model consisted of head-dependent fluxes at the northwest and southeast ends of the model grid, recharge at the top of layer 1, and no-flow conditions at the bottom of layer 3 and on the northeast and southwest sides of the model grid.

Estimated water particle linear velocities showed good correlation with the migration rate of the contaminant plume. Assuming a retardation factor of 2.0 for TCE, the computed travel time for the TCE plume to reach the northern TEAD boundary from the IWL was 20-25 years. The recalibration effort determined the likely existence of displaced sediments from seismic activity as the likely cause of the zone of low hydraulic conductivity located to the southwest of the bedrock block. The recalibrated model provided a simpler, more accurate representation of the hydrogeologic system as evidenced by the more substantial physical basis for zone delineation, the over 50-percent reduction in hydraulic conductivity zones, and the reduction in the average residual error between measured and simulated water levels from 5.3 to 3.1.

According to model simulations, the construction of three additional wells is required to ensure the simulated capture of the 5-ppb TCE contaminant plume down-gradient from the IWL. The total extraction rate required for these wells is 1,500 gpm.

Additional data-gathering efforts should focus on further delineating the bedrock block and displaced sediments which are the hydrogeological controls of the site, defining the spatial extent of vertical flow gradients in the northern alluvium, and the monitoring of water levels adjacent to extraction wells for the determination of aquifer properties.

Future recommended work to be performed on the Tooele Army Depot groundwater flow modeling study includes the transient calibration of measured versus simulated water levels after pumping begins, the application of a three-dimensional, transient particle tracking program to provide an estimate of total contaminant capture as a function of time, and the development of a simple contaminant transport model as additional improvements are made in the groundwater flow model and more water quality data become available.

14 References 79

Appendices

A. Terminology

B. 1992 Water Levels, Geomatrix

C. Surveyed Well Locations

D. Analysis of Long Term Pumping Test, Popadopolus Inc.

E. Hydrologic Characterization of Bedrock, JMM

F. Pneumatic Slug Test, Reynolds

G. Profile of Thermal and Total Dissolved Solids Gradients, JMM

H. Compilation of TEAD Groundwater Quality Assessments

I. A Computer Program Which Estimates Steady-State Drawdown at a Pumping Well Using Output from MODFLOW

J. Output of Calibrated Model Using Head-Dependent Flux Boundary Conditions Under a No-Action Scenario